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JMSS-1: a new Martian soil simulant

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Abstract

It is important to develop Martian soil simulants that can be used in Mars exploration programs and Mars research. A new Martian soil simulant, called Jining Martian Soil Simulant (JMSS-1), was developed at the Lunar and Planetary Science Research Center at the Institute of Geochemistry, Chinese Academy of Sciences. The raw materials of JMSS-1 are Jining basalt and Fe oxides (magnetite and hematite). JMSS-1 was produced by mechanically crushing Jining basalt with the addition of small amounts of magnetite and hematite. The properties of this simulant, including chemical composition, mineralogy, particle size, mechanical properties, reflectance spectra, dielectric properties, volatile content, and hygroscopicity, have been analyzed. On the basis of these test results, it was demonstrated that JMSS-1 is an ideal Martian soil simulant in terms of chemical composition, mineralogy, and physical properties. JMSS-1 would be an appropriate choice as a Martian soil simulant in scientific and engineering experiments in China's Mars exploration in the future.

Keywords: Martian soil simulant; JMSS-1; Mars analog; Mars exploration

Background

With the continuous development of the Chang'E lunar exploration program (Chang'E-1, Chang'E-2, and Chang'E-3), Mars exploration has become one of the key missions of China's deep space exploration program.

Martian soil, covering the entire surface of Mars, is an unconsolidated material which has a direct effect on the locomotion performance of the Mars Lander/Rover and the performance of other aerospace equipment (Bishop and Dummel 1996; Arvidson et al. 2004a, b). Reaching Mars and landing safely on it have proven to be challenging tasks, despite the success of recent missions (e.g., Curiosity). Therefore, in order to better prepare for orbiter and landing missions to Mars, it is essential to carry out a series of ground experiments using Martian soil before a robotic mission is launched to explore the surface of Mars (Marlow et al. 2008). However, no samples of Martian soil have been collected, even though Mars exploration activities have been carried out about 40 times within the last five decades.

In view of the lack of any Martian soil samples, a Martian soil simulant, as a substitute material for Martian soil, should be developed to replace real Martian soil to be used for scientific and engineering experiments. Martian soil simulants are usually produced using terrestrial material (e.g., basalt, volcanic ash, and volcanic cinders). It has similar chemical composition, mineralogy, particle size, and physical properties to real Martian soil. Martian soil simulants are widely used in engineering and scientific experiments in terrestrial laboratories, which mainly include payload calibration, rover walking experiments, testing and verifying of aerospace equipment, and other simulation experiments related to Mars exploration (Gross et al. 2001; Anderson et al. 2009; Beegle et al. 2009; Moroz et al. 2009; Pirrotta 2010; ElShafie et al. 2012; Merrison et al. 2012; Yeomans et al. 2013).

Four types of Martian soil simulants (JSC Mars-1, MMS, Salten Skov I, and ES-X) have been developed in the USA and at the European Space Agency for different purposes, such as spectrometer calibration, testing of lander/rover instruments, and evaluating the physical effect of Martian soil on mechanical components. JSC Mars-1, produced by the Johnson Space Center (JSC), has been widely used throughout the scientific community (Mautner and Sinaj 2002; Buhler and Calle 2003; Ormond and Kral 2006; Sharma et al. 2008). MMS (Mojave Mars Simulant) is a basaltic Mars simulant that is available as whole rock, sand, and dust. MMS sand and MMS dust are produced by mechanically crushing Saddleback basaltic boulders. They have been used in

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the development of the 2007/8 Phoenix Scout and Mars Science Laboratory mission (Peters et al. 2008). Salten Skov I is a Martian magnetic dust analog made from fine-grained magnetic iron oxide precipitate originating from Denmark. It is a good Martian dust analog in terms of grain size, magnetic properties, optical reflectance, and aggregation properties for application in wind tunnels and other dust suspension/deposition studies (Nørnberg et al. 2009). ES-X is an engineering soil produced by the European Space Agency. It has been used to test the locomotion performance of the ExoMars rover, which is planned for launch in 2018 (Brunskill et al. 2011; Gouache et al. 2011).

So far, only the USA and the European Space Agency have developed Martian soil simulants. The lack of a Martian soil simulant has limited the development of China's deep space exploration. To prepare for China's upcoming robotic mission to Mars, a new Martian soil simulant, called Jining Martian Soil Simulant (JMSS-1), has been developed. This paper describes its production process, properties, and how it compares with Martian soil and other simulants.

Methods

Target simulant and raw material selection

Martian soil is used to denote any loose, unconsolidated materials that can be distinguished from rocks, bedrock, or strongly cohesive sediments (Gellert et al. 2004). Physical weathering (e.g., impact events and wind abrasion) of a variety of intermediate to basic igneous rocks (basalts and probably basaltic andesites) is the presumed genesis of the majority of the soil, although minor chemical alterations to the source rocks and/or generated soil may occur (Wanke et al. 2001; Foley et al. 2003; Christensen et al. 2004a; Morris et al. 2004, 2006a, b; McSween et al. 2009). Data from ground-based landers/rovers and orbital spacecraft revealed that the Martian surface is dominated by basaltic soil composed primarily of pyroxene, plagioclase feldspar, and olivine, as well as minor amounts of Fe and Ti oxides (e.g., magnetite, ilmenite, and hematite) and alteration minerals (e.g., sulfates, phyllosilicates, and carbonates) (Yen et al. 2005; Morris et al. 2006a; Morris et al. 2006b; McSween et al. 2010; Bish et al. 2013). Martian surface soils measured by the Viking landers, Pathfinder, Spirit, Opportunity, and Curiosity show that the bulk chemical composition of these materials is relatively constant at widely spaced locations across the planet (Table 1).

In order to obtain a suitable Martian soil simulant that adequately represents Martian soil for engineering and scientific experiments in terrestrial laboratories, the target simulant should meet the following criteria: (1) chemical composition and mineralogy approximately similar to Martian soil; (2) particle size distribution within the range of Martian soil values (grain size = 1 to 1000 μm, median size = 250 to 300 μm); (3) bulk density and mechanical properties within the range of Martian soil values (bulk density = 1200 to 1600 g/cm^3, cohesion = 0 to 15 kPa, and internal friction angle = 20° to 40°); and (4) other properties, such as magnetic properties and reflectance spectra, similar to those of Martian soil, but not precisely imitated.

Considering the specific requirements of a Martian soil simulant, the source rock for development of the simulant was selected following these two principles: (1) it has a similar chemical composition and mineralogy to Martian basaltic rock, which contains lower levels of Al_2O_3 and higher levels of total Fe compare to terrestrial basalt, and (2) it can be easily acquired in large quantities. As a result of research and surveys, basaltic lava rock from Jining in southern Inner Mongolia was selected. It is currently being mined as construction material and is available in large quantities for the development of a Martian soil simulant (Fig. 1). The source rock for the JMSS-1 Martian soil simulant is Miocene in age and located on the northern edge of the North China craton, west of the Hannuoba basaltic field (Zhang et al. 2005). The hand samples of this basalt are dark gray to black, massive, porphyritic with fine-grained phenocrysts, and cryptocrystalline. As shown in Fig. 2, Jining basalt primarily consists of plagioclase, pyroxene, olivine, and a minor amount of ilmenite. Table 2 shows the chemical composition of Jining basalt compared to Backstay rock discovered in the Columbia Hills by the Spirit Rover and Bounce rock discovered at the Meridiani Planum by the Opportunity Rover. These results show that Jining basalt is similar to Backstay rock and Bounce rock in geochemical composition, except it is higher in Al_2O_3 and lower in total Fe (Rieder et al. 2004; McSween et al. 2006). In contrast to terrestrial basalt, Martian soil generally has a high level of total Fe (16–20 wt%). In order to produce a better simulant, magnetite and hematite, which are present in the Martian soil, were used as additives for the development of JMSS-1. The magnetite and hematite were collected from Hebei province in China.

Production of JMSS-1

JMSS-1 was produced by mechanically crushing Jining basalt with the addition of small amounts of magnetite and hematite collected from Hebei province in China. This mechanical crushing process more closely resembles the physical weathering/comminution processes of basaltic rocks on Mars, where meteoric impacts and wind abrasion are the mechanisms of comminution. The JMSS-1 Martian soil simulant was produced via the following steps: (1) coarse crushing: using a jaw crusher, the mined Jining basalt and hematite with diameters of approximately 100 to 300 mm were crushed into small rocks with diameters of <3 mm; (2) fine crushing: using

Table 1 Major element composition of JMSS-1 in comparison with Martian soil and other Martian soil simulants (wt%)

	Martian soil							Martian soil simulants		
	Viking 1[a]	Viking 2[a]	Pathfinder[b]	Spirit[c]	Opportunity[d]	Curiosity[e]	Average[f]	JSC Mars-1[g]	MMS[g]	JMSS-1
SiO_2	43.00	43.00	42.00	45.80	43.80	42.88	45.41	43.48	49.40	49.28 ± 0.24
TiO_2	0.66	0.56	0.80	0.81	1.08	1.19	0.91	3.62	1.09	1.78 ± 0.01
Al_2O_3	7.30	–	10.30	10.00	8.55	9.43	9.71	22.09	17.10	13.64 ± 0.33
Cr_2O_3	–	–	0.30	0.35	0.46	0.49	0.36	0.03	0.05	–
Fe_2O_3	18.50	17.80	21.70					16.08	10.87	16.00 ± 0.07
FeO				15.80	22.33	19.19[h]	16.73			
MnO	–	–	0.30	0.31	0.36	0.41	0.33	0.26	0.17	0.14 ± 0.01
MgO	6.00	–	7.30	9.30	7.05	8.69	8.35	4.22	6.08	6.35 ± 0.08
CaO	5.90	5.70	6.10	6.10	6.67	7.28	6.37	6.05	10.45	7.56 ± 0.06
Na_2O	–	–	2.80	3.30	1.60	2.72	2.73	2.34	3.28	2.92 ± 0.09
K_2O	<0.15	<0.15	0.60	0.41	0.44	0.49	0.44	0.70	0.48	1.02 ± 0.03
P_2O_5	–	–	0.70	0.84	0.83	0.94	0.83	0.78	0.17	0.30 ± 0.01
SO_3	6.60	8.10	6.00	5.82	5.57	5.45	6.16	0.31	0.10	–
Cl	0.70	0.50	0.90	0.53	0.44	0.69	0.68	–	–	–
LOI	–	–	–	–	–	–		17.36	3.39	0.48 ± 0.17
Total	88.81	75.81	99.80	99.37	99.18	99.85	99.01	99.70	99.40	99.47

"–" not analyzed
[a]Banin et al. (1992)
[b]Foley et al. (2003)
[c]Gellert et al. (2004)
[d]Rieder et al. (2004)
[e]Blake et al. (2013)
[f]Taylor and McLennan (2009)
[g]Peters et al. (2008)
[h]$Fe_2O_3 + FeO = 19.19$. For the Viking Landers, Pathfinder soil, JSC Mars-1, MMS, and JMSS-1 total Fe is expressed as Fe_2O_3. For Spirit and Opportunity, average soil total Fe is expressed as FeO

a ball crusher, the coarse crushed Jining basalt, magnetite, and hematite were crushed to fine grains with diameters of <1 mm; (3) mixing: these fine-grained samples were systematically mixed (93 wt% basalt, 5 wt% magnetite, and 2 wt% hematite); and (4) sieving and particle size adjustment: the grain size distribution was adjusted to achieve the target distribution by sieving the mixture.

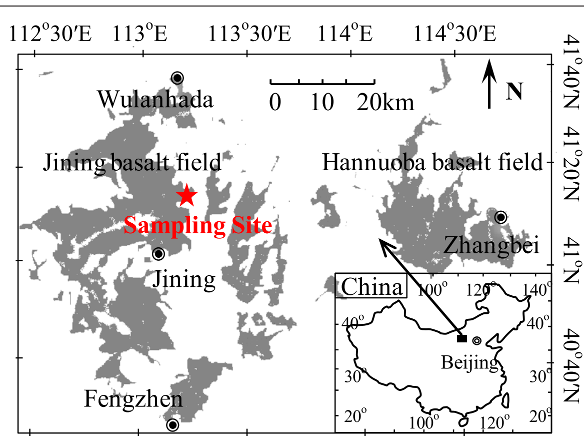

Fig. 1 Distribution of Jining basalt. The source basalt for JMSS-1 is located in Jining, southern Inner Mongolia

Analytical methods

Samples of Jining basalt and JMSS-1 were prepared and polished for scanning electron microscope analysis. Major mineral species in Jining basalt and JMSS-1 were observed and studied using a JEOL JSM-6460LV Scanning Electron Microscope operating at 15 kV at the Institute of Geochemistry, Chinese Academy of Sciences. The major element compositions of Jining basalt and JMSS-1 were analyzed by X-ray fluorescence (XRF) following standard procedures at the State Key Laboratory of Ore Deposit Geochemistry at the Institute of Geochemistry, Chinese Academy of Sciences. Samples were ground to pass a 200-mesh (75-μm) sieve prior to analysis. The particle size distribution and specific gravity of JMSS-1 were measured by a laser particle size analyzer Mastersizer 2000 and Ultrapyc 1200e gas pycnometer (Quantachrome Instruments, USA), respectively, at the Lunar and Planetary Science Research Center, Institute of Geochemistry, Chinese Academy of Sciences. The mechanical properties of JMSS-1 were determined by conventional triaxial compression (CTC) experiments at the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. The reflectance spectrum of JMSS-1 was measured at the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences.

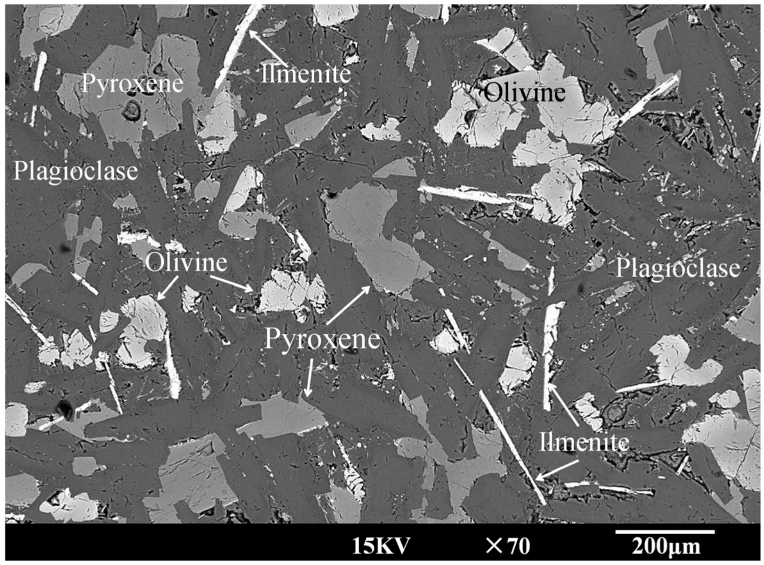

Fig. 2 Back-scattered electron image of Jining basalt. Jining basalt consists primarily of plagioclase, pyroxene, olivine, and a minor amount of ilmenite

The complex dielectric permittivity was determined by a resonant cavity perturbation method (accuracy <3 %) at 9370 MHz at the Lunar and Planetary Science Research Center, Institute of Geochemistry, Chinese Academy of Sciences (Zheng et al. 2005).

Results

Chemical composition

Table 1 provides the major element composition of JMSS-1 compared with MMS, JSC Mars-1, and descriptions of Martian soil from the Viking, Pathfinder, Spirit, Opportunity, and Curiosity landing sites. The test result for JMSS-1 is an average of three samples.

Mineralogy

From the X-ray diffraction (XRD) and scanning electron microscopy and energy dispersive spectrometry (SEM-EDS) data, JMSS-1 is mainly composed of plagioclase, pyroxene, and olivine, as well as minor amounts of ilmenite, magnetite, and hematite (Fig. 3). The composition of individual mineral phases in JMSS-1 was also determined using SEM-EDS data. The result suggested that the plagioclase, olivine, and pyroxene in JMSS-1 tend to be calcic plagioclase (~An51–An60), forsteritic olivine (~Fo56–Fo70), and augite, respectively. Table 3 lists the SEM-EDS data for typical analysis points as seen in Fig. 3. It should also be noted that no altered minerals (e.g., sulfates, clays, or carbonates) were found in JMSS-1 by XRD and SEM.

A hand magnet was used to gather the magnetic component from three samples of JMSS-1. The average magnetic component in JMSS-1 is about 5 wt%, and the magnetic phase in JMSS-1 is magnetite, as indicated by the XRD and SEM-EDS data.

Particle size and shape

A back-scattered electron image of the typical particles of JMSS-1 is shown in Fig. 3. As shown in this image, most JMSS-1 particles are angular to subangular in shape. Figure 4 presents the particle size distribution curves of JMSS-1, JSC-1 Mars-1, and MMS sand (Allen et al. 1998; Peters et al. 2008). It indicates that the grain

Table 2 Chemical composition of Jining basalt compared to Backstay rock and Bounce rock (wt%)

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Jining basalt-1	51.07	1.71	14.50	–	11.07	0.12	7.03	8.18	3.14	1.11	0.31	1.86	100.10
Jining basalt-2	51.08	1.69	14.51	–	10.93	0.13	6.89	8.05	3.14	1.09	0.30	2.20	100.01
Backstay rock[a]	50.16	0.94	13.45	0.15	13.85[c]	0.24	8.41	6.11	4.20	1.08	1.41	–	100.00
Bounce rock[b]	51.27	0.79	10.19	0.13	15.74[c]	0.43	6.46	12.62	1.31	0.10	0.96	–	100.00

"–" not analyzed
[a]McSween et al. (2006) and Nekvasil et al. (2009) (SO_3 and Cl-free, normalized to 100 %)
[b]Rieder et al. (2004) (SO_3 and Cl-free, normalized to 100 %)
[c]For Backstay rock and Bounce rock, total Fe is expressed as FeO

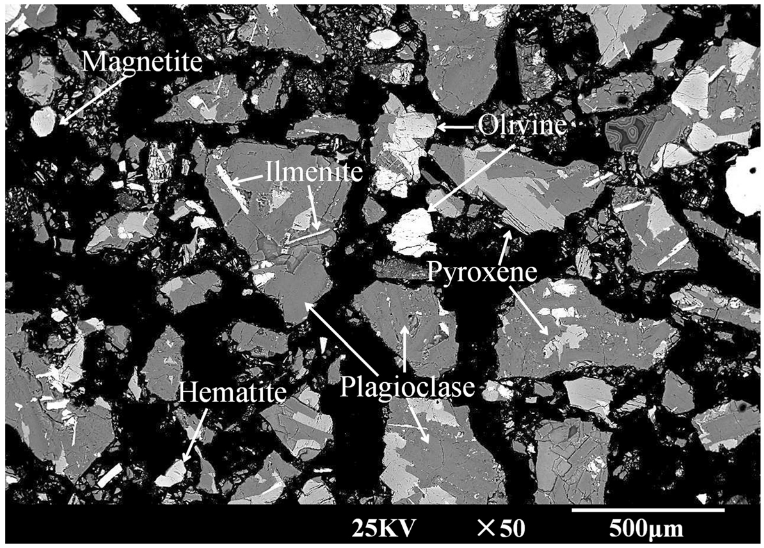

Fig. 3 Back-scattered electron image of JMSS-1. JMSS-1 consists primarily of plagioclase, pyroxene, and olivine, as well as minor amounts of ilmenite, magnetite, and hematite. Most JMSS-1 particles are angular to subangular in shape

size of JMSS-1 is <1 mm, and the median and mean particle sizes of this sample are ~300 and ~250 μm, respectively.

Mechanical properties

Table 4 presents the mechanical properties of JMSS-1 compared to MMS, JSC Mars-1, and Martian regolith observed at different Mars landing sites.

The specific gravity is the ratio of particle mass to the mass of an equal volume of water at 4 °C. Measured for three JMSS-1 samples, the average specific gravity of JMSS-1 particles is 2.88 g/cm^3. We measured the masses and volumes of several JMSS-1 samples to determine a mean bulk density of 1.45 g/cm^3. This value, compared to the particle density, infers a porosity of 49.65 % for JMSS-1.

Table 3 Representative SEM-EDS data of major phases in JMSS-1 (wt%)

	Olivine	Pyroxene	Plagioclase	Ilmenite	Magnetite	Hematite
SiO_2	37.69	52.95	52.25	2.43	1.38	0.78
TiO_2	0.19	0.75	0.15	47.05	0.25	0.39
Al_2O_3	0.25	2.74	28.96	0.78	0.53	0.15
Cr_2O_3	0.1	0.75	0.15	0.09	0.18	0.7
Fe_2O_3	29.48	7.18	0.93	47.43	94.83	96.84
MnO	0.48	0.18	0.06	0.57	0.45	0.91
MgO	30.87	16.12	1.16	0.62	0.89	0
CaO	0.41	18.25	10.99	0.36	0.34	0.18
Na_2O	0.39	0.6	4.06	0.27	0.35	0
K_2O	0.14	0.11	0.39	0.3	0.35	0.05
P_2O_5	0	0.35	0.91	0.1	0.44	0

The angle of internal friction of JMSS-1 is approximately 40.6°, and the cohesion of this material is approximately 0.33 kPa. Figure 5 shows the Mohr stress circles which were used to determine the angle of internal friction and cohesion for of JMSS-1.

Reflectance spectra

The visible to near-IR spectra of JMSS-1, MMS sand, and JSC Mars-1 are shown in Fig. 6 (Allen et al. 1998; Peters et al. 2008). The reflectance spectrum of JMSS-1 is similar to those of JSC Mars-1 and MMS sand. Each has a rise in reflectance value from 400 to 700 nm, with an absorption band in the 900- to 1100-nm region, and

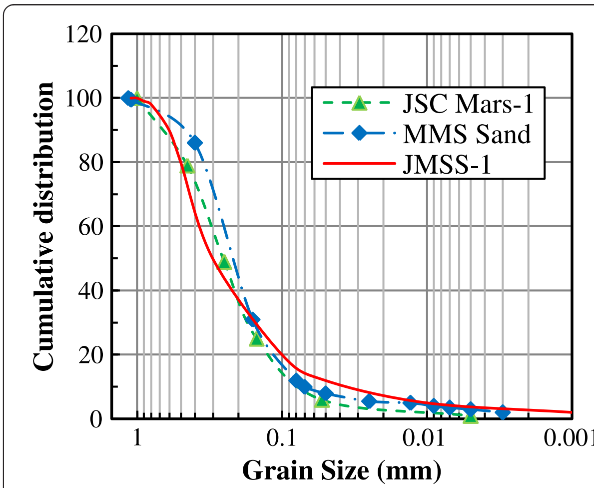

Fig. 4 Particle size distributions of JMSS-1, JSC Mars-1, and MMS sand. JMSS-1 (*red curve*) has a particle size distribution similar to those of JSC Mars-1 (*green curve*) and MMS sand (*blue curve*)

Table 4 Mechanical properties of JMSS-1, MMS, JSC Mars-1, and Martian regolith at different Mars landing sites

	Soil type	Bulk density (kg/cm^3)	Cohesion (kPa)	Internal friction angle (°)
JMSS-1	Soil simulant	1450	0.33	40.6
MMS sand[a]	Soil simulant	1341–1384	0.81–1.96	38–39
MMS dust[a]	Dust analog	911–1078	0.38–0.53	30–31
JSC Mars-1[b]	Soil simulant	835	1.91	47
Spirit Rover[c]	Drift material	1200–1500	1–15	~20
Opportunity Rover[d]	Surface soil	~1300	1–5	~20
Pathfinder[e]	Drift material	1285–1518	0–0.42	34.3
Pathfinder[e]	Crusty material	1422–1636	0.17 ± 0.18	37.0 ± 2.6
Viking Lander 1[f]	Drift material	1150 ± 150	1.6 ± 1.2	18.0 ± 2.4
Viking Lander 1[f]	Blocky material	1600 ± 400	5.1 ± 2.7	30.8 ± 2.4
Viking Lander 2[f]	Crusty material	1400 ± 200	1.1 ± 0.8	34.5 ± 4.7

[a]Peters et al. (2008)
[b]Allen et al. (1998)
[c]Arvidson et al. (2004a)
[d]Arvidson et al. (2004b)
[e]Moore et al. (1999)
[f]Moore and Jakosky (1989)

a generally flat reflectance from 1000 to 2400 nm as shown in Fig. 7. The existence of a band at 1900 nm in these simulant spectra is likely due to the presence of OH and H_2O.

Dielectric properties

Measurements of the dielectric properties of Martian soil simulant and other materials can help to anticipate radar performance on Mars, because radar signal penetration is influenced by the dielectric properties of the penetrated materials (Olhoeft and Capron 1993; Williams and Greeley 2004). The dielectric constant (ε') and loss ($\tan\delta$) of JMSS-1 at 9370 MHz are about 5.9 and 0.07 (accuracy < 3 %), respectively.

Volatile content and hygroscopicity

In order to determine the volatile content of JMSS-1, a 10-g JMSS-1 sample was prepared for a heating experiment in a high-temperature furnace. The weight losses of JMSS-1 after 1 h range from ~1.49 wt% at 100 °C to ~4.7 wt% at 500 °C. These results represent total volatile loss, which is probably dominated by H_2O.

The hygroscopic property of the Martian soil simulant is an important parameter in experiments and tests, because its physical properties will probably change with the absorption of water. We prepared a 10-g JMSS-1 sample during a moderately humid day (20 °C and 50 % relative humidity). This sample was then place in a tank at a temperature of 20 °C and a humidity of 80 %. Its

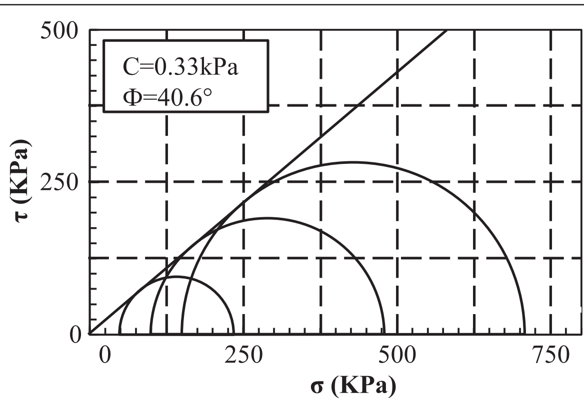

Fig. 5 CTC experiment of JMSS-1 Mohr stress circles. Mohr stress circles used to determine the angle of internal friction (40.6°) and cohesion (0.33 kPa) for JMSS-1

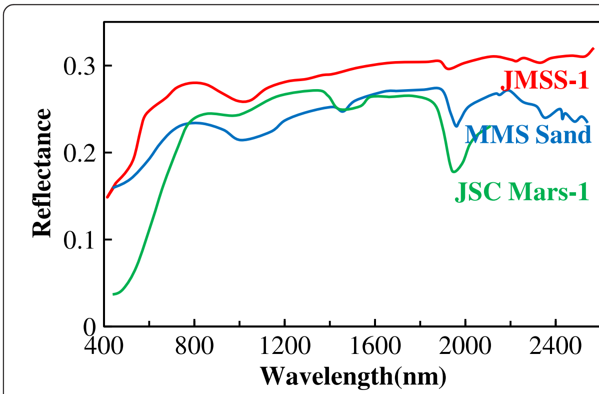

Fig. 6 Reflectance spectra of JMSS-1, JSC Mars-1, and MMS sand. Reflectance spectra of JMSS-1 (*red curve*) are similar to those of JSC Mars-1 (*green curve*) and MMS sand (*blue curve*) in the 400- to 2500-nm region

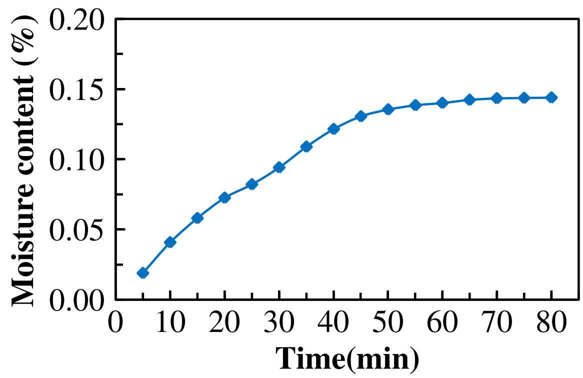

Fig. 7 Hygroscopic property of JMSS-1. JMSS-1 absorbs moisture relatively fast in the initial phase, and its moisture content reaches approximately 0.14 % after 70 min

moisture content was measured every 5 min until the moisture content became approximately constant. Figure 7 presents the variation of moisture content against time, which indicates the hygroscopic property. During a 5-min period, JMSS-1 gained approximately 0.018 wt%. The moisture content then became approximately constant at 0.14 wt% after 70 min.

Discussion

Comparison with Martian soil

Much of the Martian surface is covered by unconsolidated soils derived from a variety of impact, eolian, and thermal cycle stresses, as well as chemical alterations, including reaction of the sulfate and/or ferric phases and salts with water provided either by the diurnal moisture variations over long time periods or by other more speculative forms of water (Bishop et al. 2002; Blake et al. 2013). Despite the presence of secondary alteration minerals, the ubiquity of olivine and pyroxene in Martian soil suggests that physical weathering has dominated over chemical weathering during the time that Martian soil has been exposed on the surface (Christensen et al. 2004b; McGlynn et al. 2012). JMSS-1 has undergone a mechanical crushing process that more closely resembles the physical weathering processes on Mars, where meteoric impact and wind abrasion provide mechanisms for comminution. This means that JMSS-1 more closely resembles the physical weathering product of basaltic rocks of Mars.

As shown in Table 1, Martian soil measured at six different landing sites shows homogeneity amongst its main chemical components. However, there are also regional and trace components in Martian soil, such as carbonate, chlorohydrocarbon, and glassy spherules identified at the Gale Crater (Blake et al. 2013; Leshin et al. 2013; Minitti et al. 2013). In situ measurements of soil samples indicate that Martian soil contains approximately 43–45 wt% SiO_2, 16–20 wt% FeO, 7–10 wt% Al_2O_3, 6–9 wt% MgO, 6–8 wt% CaO, 0.7–0.9 wt% P_2O_5, and 5–8 wt% SO_3 (Banin et al. 1992; Foley et al. 2003; Gellert et al. 2004; Rieder et al. 2004; Blake et al. 2013). As shown in Table 1, compared to Martian soil, JMSS-1 has higher levels of SiO_2 (49.28 wt%) and Al_2O_3 (13.64 wt%) and lower levels of SO_3 and P_2O_5 (0.3 wt%).

Based on data from Mars rovers (Spirit, Opportunity, and Curiosity), Martian surface soil consists primarily of plagioclase, pyroxene, and olivine, with minor amounts of Fe and Ti oxides (e.g., magnetite, ilmenite, and hematite) and various alteration minerals (e.g., sulfates, phyllosilicates, and carbonate) (Yen et al. 2005; McSween et al. 2010; Bish et al. 2013). As for the composition of individual mineral phases in Martian soil at the Spirit, Opportunity, and Curiosity landing sites, plagioclase tends to be sodic to intermediate (~An57) in composition, olivine tends to be forsteritic olivine (~Fo62), and pyroxene tends to favor Ca-rich pyroxene (e.g., augite) with subordinate amounts of Ca-poor pyroxene (e.g., pigeonite) (Christensen et al. 2004a, b; Bish et al. 2013). These results are consistent with the mineralogy of JMSS-1, which is also dominated by plagioclase, pyroxene, and olivine, with minor amounts of magnetite, ilmenite, and hematite. In addition, the individual mineral phases in JMSS-1 tend to be calcic plagioclase (~An51–An60), forsteritic olivine (~Fo56–Fo70), and augite, respectively. These results demonstrate that JMSS-1 is a good mineralogical analog for the igneous mineral composition of Martian soil. It should be noted that JMSS-1 does not contain the alteration minerals that have been found in Martian soil. In order to simulate Martian soil more accurately, minor amounts of alteration minerals (e.g., sulfates, carbonates, and clays) need to be added to JMSS-1 in future work.

The Viking and Pathfinder missions estimated the magnetic materials in Martian soil to be 1–7 wt% (Hargraves et al. 1977; Madsen et al. 1999; Bertelsen et al. 2004). Magnetite is thought to be the main magnetic phase in Martian regolith, and hematite is thought to be responsible for the red surface of Mars (Hargraves et al. 1977, 1979; Moore and Jakosky 1989; Hviid et al. 1997; Madsen et al. 1999, 2003). This is consistent with JMSS-1, which has an average magnetic component (magnetite) of ~5 and ~2 wt% hematite.

Based on data from the Mars landers/rovers (Table 4), the bulk density and mechanical properties of JMSS-1 are within the range of Martian soil values. The grain size of JMSS-1 is also similar to Martian soil, with a particle size of approximately 10–500 μm observed by Viking, Pathfinder, Spirit, and Opportunity (Moore and Jakosky 1989; Moore et al. 1999; Golombek et al. 2008).

Comparison with other reported simulants

By way of comparison, JMSS-1 has similar chemical composition, mineralogy, and physical properties to the

Martian soil simulant currently in common use (JSC Mars-1 and MMS).

JSC Mars-1 is an altered volcanic ash mainly composed of plagioclase, along with minor Ti magnetite, Ca-rich pyroxene, olivine, glassy, ferric oxide particles, and less than 1 wt% of crystalline clay minerals or phyllosilicates (Allen et al. 1998). The significant difference between JSC Mars-1 and JMSS-1 is that JMSS-1 is largely crystalline and contains more pyroxene, olivine, and hematite, while JSC Mars-1 is primarily glassy in texture and contains ferric oxide particles. In addition, JMSS-1 has low levels of TiO_2 and Al_2O_3 and higher levels of SiO_2 and MgO compared to JSC Mars-1 (Table 1).

Compared to MMS, JMSS-1 contains less Al_2O_3 and CaO and more Fe_2O_3 (Table 1). The mineral composition of JMSS-1 is in agreement with that of MMS, which mainly consists of plagioclase and pyroxene, along with minor olivine, ilmenite, and hematite (Peters et al. 2008).

As for the magnetic properties, JMSS-1 contains ~5 wt% magnetite, which is the main magnetic phase in Martian regolith, whereas JSC Mars-1 has ~25 wt% Ti magnetite, and the weak magnetic mineral phases in MMS are most likely ilmenite and hematite (Moore and Jakosky 1989; Allen et al. 1998; Madsen et al. 1999; Bertelsen et al. 2004; Morris et al. 2006b; Peters et al. 2008).

The bulk density of JMSS-1 is significantly greater than those of JSC Mars-1 and MMS (Table 4), which is probably due to the addition of magnetite and hematite.

The volatile loss of JMSS-1 was ~1.49 wt% at 100 °C and ~4.7 wt% at 500 °C. This result is consistent with MMS, which has a volatile loss of 1.7 wt% at 100 °C, 7.2 wt% at 500 °C, and lower than values for JSC Mars-1 (volatile loss ranging from 7.8 wt% at 100 °C to 21.1 wt% at 600 °C) (Allen et al. 1998; Peters et al. 2008).

Conclusions

We identified a basaltic rock in China that is available as raw material for the development of a Martian soil simulant. A new Martian soil simulant, JMSS-1, was produced by mechanically crushing Jining basalt with the addition of small amounts of magnetite and hematite. This simulant has undergone a mechanical comminution process that closely resembles the physical weathering processes on Mars where meteoric impact and wind abrasion are the mechanisms for comminution. JMSS-1 has similar chemical composition, mineralogy, and physical properties to Martian basaltic soil and can be used for the testing of Mars landers/rovers, the development of future instruments, and other scientific and engineering experiments in China's Mars exploration program.

Abbreviation

JMSS-1: Jining Martian Soil Simulant.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

XZ prepared the samples, carried out the property measurements, and drafted the manuscript. XL and SW conceived the study. NS helped to edit the manuscript. SL, YL, HT, and JF participated in the design of the experiment. All authors read and approved the final manuscript.

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